A Motion-Control Chip to Generate Velocity Profiles of Desired Characteristics

Jung Uk Cho and Jae Wook Jeon

A motion-control chip contains major functions that are necessary to control the position of each motor, such as generating velocity command profiles, reading motor positions, producing control signals, driving several types of servo amplifiers, and interfacing host processors. Existing motion-control chips can only generate velocity profiles of fixed characteristics, typically linear and s-shape smooth symmetric curves. But velocity profiles of these two characteristics are not optimal for all tasks in industrial robots and automation systems. Velocity profiles of other characteristics are preferred for some tasks. This paper proposes a motion-control chip to generate velocity profiles of desired acceleration and deceleration characteristics. The proposed motion-control chip is implemented with a field-programmable gate array by using the Very High-Speed Integrated Circuit Hardware Description Language and Handel-C. Experiments using velocity profiles of four different characteristics will be performed.

Keywords: Motion-control chip, velocity profile.

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I. Introduction

Position controllers have been used to control the position of motors in industrial robots and automation systems. Nowadays, board level motion controllers have been most widely used. These board level motion controllers include software motion libraries and interface circuits to servo amplifiers and host computers. Additional software for these board level motion controllers is also provided to make it easy to control and coordinate each motor. In cases where smaller size and lower cost are desired, a chip level motion controller using a motion-control chip is preferred because the motion-control chip includes motion related circuits and interface circuits. But existing motion-control chips can only generate velocity profiles of fixed characteristics, typically linear and s-shape smooth symmetric curves [1]-[9]. In order to make industrial robots and automation systems move more accurately and more quickly, one of the important factors is efficiently generating velocity profiles that have the desired acceleration and deceleration characteristics, which in turn are determined by given tasks. Several features of velocity profiles of various acceleration and deceleration characteristics were discussed in [5]. Since existing motion-control chips cannot generate velocity profiles of some acceleration and deceleration characteristics, they cannot perform all tasks in industrial robots and automation systems efficiently.

This paper proposes a motion-control chip to generate velocity profiles of desired acceleration and deceleration characteristics for performing a given task efficiently. The proposed motion-control chip consists of six modules: a velocity profile generator, a feedback counter, a controller, a data converter, an external interface, and a clock generator. The velocity profile generator module can efficiently generate velocity profiles of desired acceleration and deceleration characteristics. The feedback counter module reads the current motor position and has a filter to eliminate the glitch type noises of encoder signals. The controller module designed by using the proportional integral derivative (PID) control law can make the motor position follow its command. The data converter module produces suitable signals for various types of servo amplifiers. The external interface module communicates with a host PC or processors. The clock generator module supplies timings in the motion-control chip. By using the Very High-Speed Integrated Circuit Hardware Description Language (VHDL) and Handel-C, the proposed motion-control chip for industrial robots and automation systems is implemented with a field-programmable gate array (FPGA).

In section II, a technique that can efficiently generate velocity profiles of desired acceleration and deceleration characteristics is explained [10]-[12]. In section III, the design of a motion-control chip to generate velocity profiles of desired acceleration and deceleration characteristics is described. The function of each internal block in the modules is explained. In section IV, the proposed motion-control chip is implemented with an FPGA. One chip-based motion controller is built by using the proposed motion-control chip and is used to control a single-axis system. Velocity command profiles of four different characteristics generated by the proposed motion-control chip are applied to the single-axis control system. The corresponding responses are measured. Our conclusions are described in section V.

II. A Technique to Generate Velocity Profiles of Desired Characteristics

Let us consider a single-axis control system of which the maximum velocity and sampling time are V_{max} and T_s, respectively. Let $f_a(u)$ and $f_d(u)$ represent the desired acceleration and deceleration characteristics, respectively, where $f_a(0)=0$, $f_a(1)=1$, $f_d(0)=1$, $f_d(1)=0$, and $\underset{0\le u\le 1}{\mathrm{Max}}|f_a(u)| = \underset{0\le u\le 1}{\mathrm{Max}}|f_d(u)| = 1$. For some integers n_a and n_d, defining

$$^{a}\gamma_k = n_a \int_{(k-1)/n_a}^{k/n_a} f_a(u)du \quad \text{for} \quad k=1,2,\ldots,n_a \tag{1}$$

and

$$^{d}\gamma_k = n_d \int_{(k-1)/n_d}^{k/n_d} f_d(u)du \quad \text{for} \quad k=1,2,\ldots,n_d, \tag{2}$$

$^{a}\gamma_k$ can be calculated from n_a and the desired acceleration characteristic, and $^{d}\gamma_k$ can be calculated from n_d and the desired deceleration characteristic. They can be stored in advance. Likewise, defining

$$\alpha_a = \int_0^1 f_a(u)du \tag{3}$$

and

$$\alpha_d = \int_0^1 f_d(u)du\,, \tag{4}$$

α_a and α_d can also be calculated from the desired acceleration and deceleration characteristics, respectively, and can be stored in advance.

Given acceleration interval $T_a=n_aT_s$, deceleration interval $T_d=n_dT_s$, and distance S, a velocity profile of the acceleration characteristic, $f_a(u)$, and the deceleration characteristic, $f_d(u)$, can be generated as follows:

(i) Coefficients determined by the intervals and characteristics of acceleration and deceleration, $^{a}\gamma_1, {}^{a}\gamma_2, \ldots, {}^{a}\gamma_{n_a}$, $^{d}\gamma_1, {}^{d}\gamma_2, \ldots, {}^{d}\gamma_{n_d}$, α_a, and α_d are retrieved.

(ii) For moving distance S, the velocity after acceleration V_m is determined as

$$V_m T_s = \begin{cases} \dfrac{S}{\alpha_a n_a + \alpha_d n_d} & \text{if} \quad N \le 0, \\ \dfrac{S}{N + \alpha_a n_a + \alpha_d n_d} & \text{if} \quad N > 0, \end{cases} \tag{5}$$

where $$N = \left\lceil \frac{S}{V_{max}T_s} - \alpha_a n_a - \alpha_d n_d \right\rceil. \tag{6}$$

(iii) Then, the position increment during each sampling time is calculated as follows:

if $N \le 0$,

$$\delta P(kT_s) = \begin{cases} {}^{a}\gamma_k V_m T_s, & 1 \le k \le n_a, \\ {}^{d}\gamma_{(k-n_a)} V_m T_s, & n_a + 1 \le k \le n_a + n_d, \end{cases} \tag{7}$$

if $N > 0$,

$$\delta P(kT_s) = \begin{cases} {}^{a}\gamma_k V_m T_s, & 1 \le k \le n_a, \\ V_m T_s, & n_a + 1 \le k \le n_a + N, \\ {}^{d}\gamma_{(k-n_a-N)} V_m T_s, & n_a + N + 1 \le k \le n_a + N + n_d. \end{cases} \tag{8}$$

Since coefficients $^{a}\gamma_1, {}^{a}\gamma_2, \ldots, {}^{a}\gamma_{n_a}$, $^{d}\gamma_1, {}^{d}\gamma_2, \ldots, {}^{d}\gamma_{n_d}$, α_a, and α_d have been calculated and stored in advance, the velocity profile of the desired acceleration and deceleration characteristics can be efficiently calculated for a given distance. Since the coefficients $^{d}\gamma_1, {}^{d}\gamma_2, \ldots, {}^{d}\gamma_{n_d}$ can be selected independently from the coefficients $^{a}\gamma_1, {}^{a}\gamma_2, \ldots, {}^{a}\gamma_{n_a}$, the deceleration characteristics can be made to be independent from the acceleration characteristics.

III. Proposed Motion-Control Chip

A motion-control chip is designed as shown in Fig. 1, which consists of six modules: a velocity profile generator (VPG), a feedback counter, a controller, a data converter, an external interface, and a clock generator.

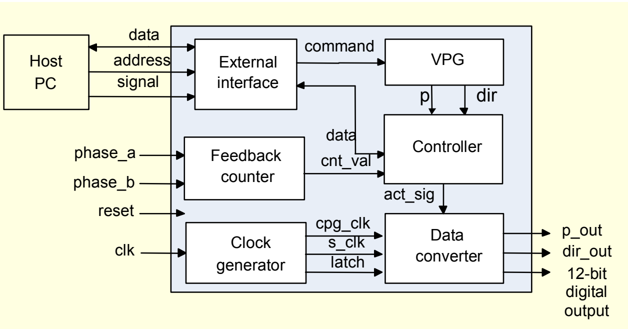

Fig. 1. Proposed motion-control chip.

1. Velocity Profile Generator

The VPG module in the proposed motion-control chip is based on the technique in section II, which can generate any desired velocity profile efficiently [10]-[13]. Figure 2 shows the architecture of the VPG module. Its inputs, V_{max} and S, represent the maximum velocity and desired distance to move, respectively. Another input, C_v, represents the intervals and characteristics of acceleration and deceleration. Its outputs, p and *dir*, represent the command pulse and rotation direction of a motor, respectively. Parameters *clk* and *cpg_clk* represent the input clock and the clock for the block, CPG (command pulse generator), respectively. The other parameters, *reset*, *enable*, and *latch*, represent control signals.

The block, SIGN, calculates the rotation direction of a motor, *dir*, and the desired distance magnitude, $|S|$, from the desired distance, S. The block, PVG (peak velocity generator), calculates the velocity after the acceleration, V_m, the distance during the deceleration, S_d, and the initial and final values of the block, Counter. The velocity after the acceleration, V_m, is calculated as in (5) and (6). Division operations in the PVG block are implemented by using Handel-C. The distance during the deceleration is calculated as $S_d = a_d n_d V_m T_s$ from (4). The initial and final values of the Counter block are determined by desired acceleration and deceleration characteristics. The Counter block generates the address of the block, RFG (rate factor generator). The address is increased and decreased during acceleration and deceleration, respectively. The address remains constant during a uniform velocity interval. The RFG block stores the product of each desired characteristic coefficient γ_k and 128 to avoid a floating-point calculation, and it sends each product value to the block, PI (position increment). The PI block calculates the position increment during each sampling time as in (7) and (8). The output of block PI is the product of a real position increment and 128 because the output of block RFG is the product of a coefficient and 128. The block, RPC (remaining pulse calculator) calculates the remaining distance, S_r, by decrementing $|S|$ by each command pulse p. The block, Comparator 1, compares this remaining distance with the distance during deceleration, S_d, in order to detect when the deceleration starts. The block, Comparator 2, compares this remaining distance with the zero value in order to detect when the motor stops. Figure 3 shows block CPG, which produces command pulse p. This block is similar to a digital differential analyzer and performs a division of 128 in order to compensate for the multiplication of 128 in block RFG [5].

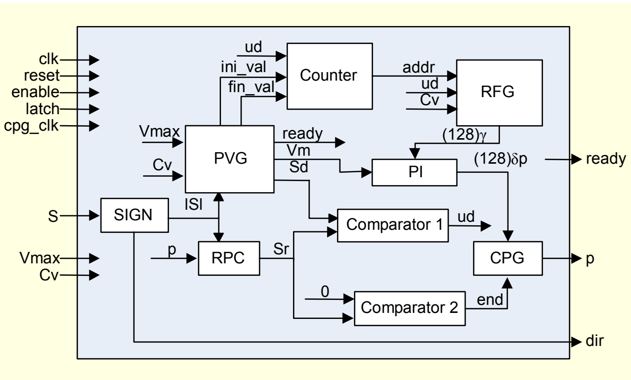

Fig. 2. Velocity profile generator.

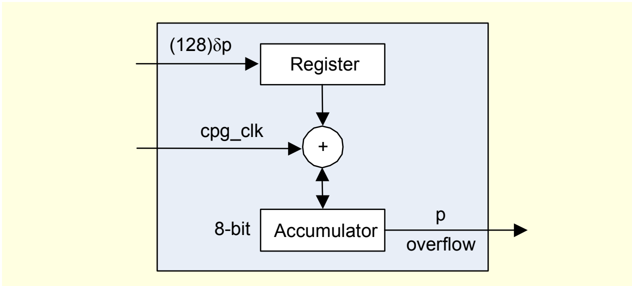

Fig. 3. Command pulse generator.

2. Feedback Counter

The feedback counter module calculates the current motor position, *cnt_val*, from encoder signals, *phase_a* and *phase_b*, by using a 32-bit counter. Since encoder signals may contain glitch type noises, a digital delay filter as in Fig. 4 is included to eliminate them, where a 2-of-3 voting technique is applied. The clock of this digital delay filter is dependent on the maximum output frequency of the encoder.

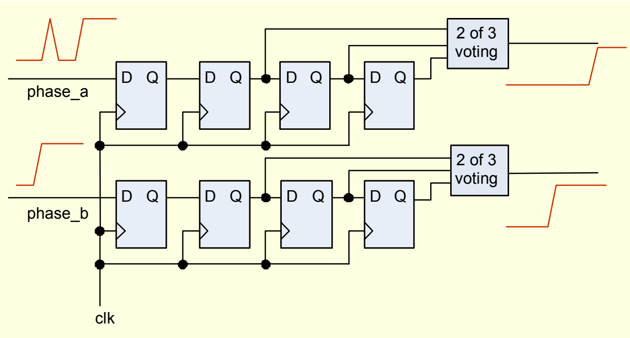

Fig. 4. Digital delay filter.

3. Controller

Figure 5 shows the architecture of the controller module. The block, Integrator, accumulates the command pulse *p* of the VPG module depending on the rotational direction output *dir* of the VPG module. For example, its value is increased and decreased under the counterclockwise and clockwise rotations, respectively. The PID Controller block generates a PID control output, *act_sig*, and sends it along with the current motor position, *cnt_val*, and the accumulated value of VPG module command pulses, *ip*, to the block, DT (data transmitter). The host PC sends the gain values of the PID Controller block. The DT block converts the values from the PID Controller block into suitable forms for the host PC and data converter module. Also, the DT block generates interrupt signals in order to send these converted values to the host PC through the PCI bus.

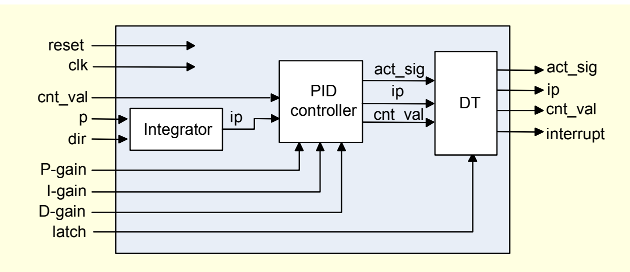

Fig. 5. Controller.

4. Data Converter

The data converter module converts the PID control output into driving signals for servo amplifiers of several types. For two-channel pulse-based servo amplifiers, it can produce signals, *p_out* and *dir_out*, which represent the pulse and direction, respectively. For digital servo amplifiers and a digital-to-analog converter of analog servo amplifiers, it can also produce a 12-bit digital value output.

5. External Interface

Figure 6 shows the connection of the external interface module with other modules in detail. Since the external interface module contains a PCI-to-PCI bridge function, the proposed motion-control chip can communicate with the host PC through the PCI bus. The desired distance command, the maximum motor velocity, the velocity profile characteristics, and the gains of the PID control are transferred from the host PC to the motion-control chip. The accumulated value of the VPG module output pulses and the current motor position are transferred from the motion-control chip to the host PC.

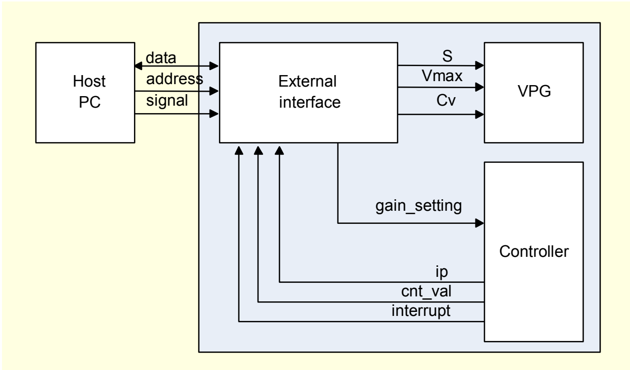

Fig. 6. External interface.

6. Clock Generator

The clock generator module provides the sampling clock, *s_clk*, the clock for the CPG block, *cpg_clk*, and some timing signals for the proposed motion-control chip.

IV. Experiment

In order to implement the proposed motion-control chip, a Xilinx FPGA, XC2S600E-6FG456, that has 600 K system gates, 15,552 logic cells, and 392 I/O pins has been used. The device utilization when this chip implements the proposed motion-control chip is as shown in Table 1. A chip-based motion controller is made with this FPGA-based motion-control chip and a few ICs as in Fig. 7. A single-axis control system as in Fig. 8 consists of a PC, a chip-based motion controller, a servo amplifier CSA11-012SR12R, and one AC servo motor [14]. The host PC sends the desired distance command, the maximum motor velocity, the velocity profile characteristics, and the gains of PID control and receives some information about this one-axis control system such as the desired pulses per sampling time in a velocity command profile, the current motor position, and the output of PID controller by using an interrupt. The rated power, rated torque, and rated speed of the motor are 30 watt, 1.0 kg·cm, and 3,000 rpm, respectively. The resolution of its encoder is 4,096 pulses/rev. The load of this motor is an iron disk, of which the radius

Table 1. Device utilization.

Design Summary
Number of errors: 0
Number of warnings: 14
Logic Utilization:
Total Number Slice Registers : 867 out of 13,824 6%
Number used as Flip Flops: 775
Number used as Latches: 92
Number of 4 input LUTs: 7,182 out of 13,824 51%
Logic Distribution:
Number of occupied Slices: 4,989 out of 6,912 72%
Number of Slices containing only related logic: 4,989 out of 4,989 100%
Number of Slices containing unrelated logic: 0 out of 4,989 0%
*See NOTES below for an explanation of the effects of unrelated logic
Total Number 4 input LUTs: 8,221 out of 13,824 59%
Number used as logic: 7,182
Number used as a route-thru: 1,038
Number used as Shift registers: 1
Number of bonded IOBs: 89 out of 325 27%
IOB Flip Flops: 35
Number of Tbufs: 64 out of 7,104 1%
Number of GCLKs: 2 out of 4 50%
Number of GCLKIOBs: 2 out of 4 50%
Total equivalent gate count for design: 79,954
Additional JTAG gate count for IOBs: 4,368
Peak Memory Usage: 145 MB

Fig. 7. A chip-based motion controller.

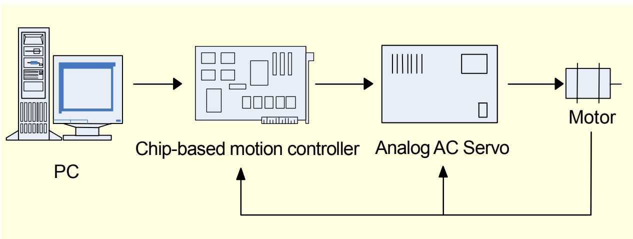

Fig. 8. A single-axis control system.

Table 2. Characteristics of the velocity profiles.

Characteristics	Acceleration $0 \le u \le 1$	Deceleration $0 \le u \le 1$
Linear (Trapezoidal)	u	$1-u$
Symmetric smooth I (S-shape)	$\frac{1}{2}\left(\sin(\pi(u-\frac{1}{2}))+1\right)$	$\frac{1}{2}\left(\sin(\pi(u-\frac{3}{2}))+1\right)$
Symmetric smooth II (Bell-shape)	$\sin(\frac{\pi}{2}u)$	$\cos(\frac{\pi}{2}u)$
Unsymmetrical smooth	$\sin(\frac{\pi}{2}u)$	$\frac{1}{2}\left(\sin(\pi(u-\frac{3}{2}))+1\right)$

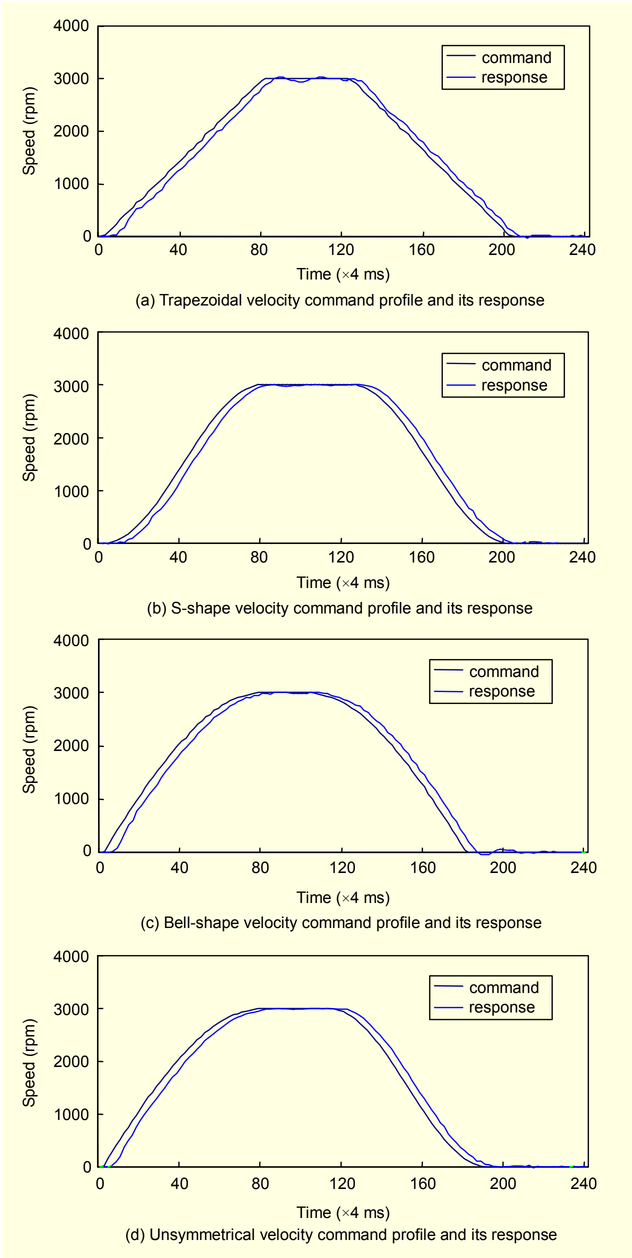

Fig. 9. A single-axis control system.

and the thickness are 40 and 8 mm, respectively. The sampling time of this single-axis control system is 4 ms. The system input clock frequency is 24.576 MHz. The acceleration and deceleration times are 320 ms. The desired distance to move is 100,000 pulses. In order to make a motor move the desired distance, velocity profiles of four different characteristics as in Table 2 are generated by the proposed motion-control chip. Among these velocity profiles, the bell-shape symmetric smooth and unsymmetrical velocity profiles cannot be generated by the existing motion-control chip [10], [15]. These velocity profiles have been applied to control a single-axis system. Figure 9 shows the results of the position control under a proportional control with gain 96/256.

V. Conclusion

Since velocity profiles of fixed acceleration and deceleration characteristics are not optimal for all tasks of industrial robots and automation systems, velocity profiles of various characteristics need to be generated. That is, given a task, velocity profiles of appropriate acceleration and deceleration characteristics should be selected. For example, applying velocity profiles of the unsymmetrical smooth acceleration and deceleration characteristics to an industrial assembly robot system, the time to perform an assembly task can be reduced [15]. Since the proposed motion-control chip can generate velocity profiles of desired acceleration and deceleration characteristics, it can be used for a wide range of motor position control. Also, it helps to make a smaller, lower cost, and lower power motion controller.

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